Advanced Process Characterization using Light Source Performance Modulation and Monitoring

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ABSTRACT

As DUV multi-patterning requirements continue to become more stringent, it is critical that all sources of lithography patterning variability are characterized and monitored. Advanced process characterization studies have been enabled using Cymer's novel technique to modulate Beam Divergence and Polarization, and Energy, Bandwidth, or Wavelength light source performance. These techniques have been instrumental in helping identify process sensitivities that enable proactive light source monitoring and excursion detection using SmartPulse™.

Demonstration of the benefits of these technologies is provided through results from recent experiments at imec. Changes in patterning performance are characterized using top down CD-SEM metrology, enabling excellent correlation between optical parameters and on wafer attributes for typical patterning geometries. In addition, new results show that changes in laser beam parameter performance can have measurable wafer patterning and/or illumination impacts. Chipmakers can benefit from the use of this capability to perform proactive, comprehensive characterization of current and next generation process nodes.

KEYWORDS: Optical Lithography, Excimer Laser, E95, Bandwidth, Beam Divergence, Depth of Focus, Process Window

1. INTRODUCTION

ArF-immersion lithography solutions continue to provide the foundation for advanced lithography patterning and are the primary drivers for High Volume Manufacturing (HVM) and ITRS technology roadmaps[1-2], see Figure 1. Based on current technology trends, advanced process nodes will be primarily based on ArF-immersion multiple patterning utilizing advanced exposure systems[3-6], SMO (source-mask optimization)[7], and applications-specific corrections[8-10].

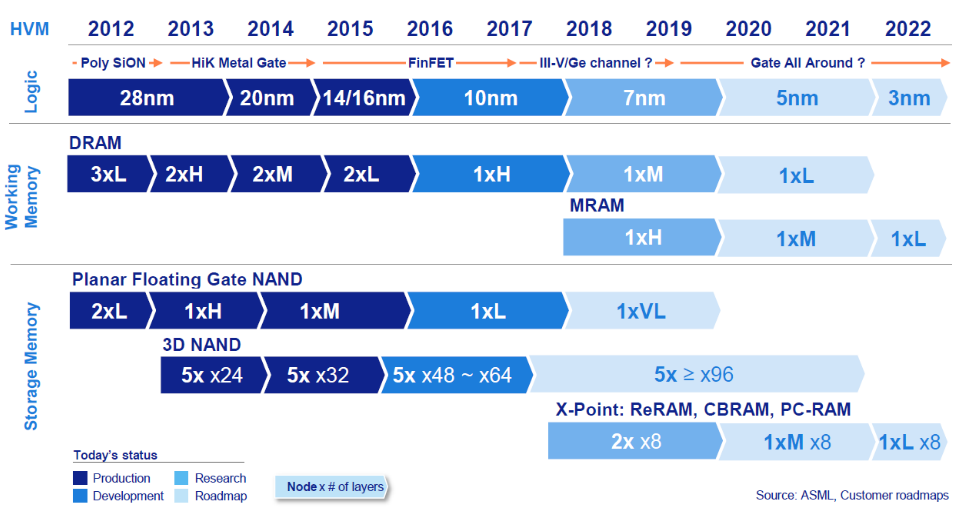


Figure 1. Chip Maker Roadmap Overview

Previous studies, as presented at SPIE Advanced Lithography Conferences[11-12], investigated the impact of beam and optical parameter light source performance on scanner illumination and 1D and 2D patterning for ≤ 20 nm process nodes. These experimental results showed that light source performance can impact patterning, and highlighted the importance of light source performance monitoring to ensure process stability. For example, as shown in Figure 2, beam divergence and polarization changes were found to significantly impact contact hole patterning (left) and variation in E95 bandwidth performance was identified as a key modulator of complex 2D structure patterning (right).

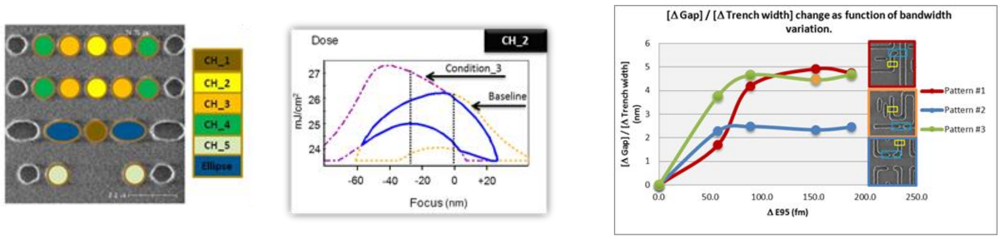


Figure 2. Beam (left) and Optical (right) performance modulation experiment results on ≤ 2x nm process node contact holes and 2D structures, respectively

As devices and lithography requirements are predicted to scale until at least 2020, advanced node structures created with ArF immersion based multiple patterning techniques will continue to be used. This study is focused on assessing future customer imaging needs with known light source imaging performance metrics.

2. PROCESS SENSITIVITY CHARACTERIZATION

2.1 Experimental Conditions

The experiments reported in this paper were performed at imec's 300 mm facility using an ASML NXT:1950i ArFi scanner and a Cymer XLR-660ix light source with Cymer's SmartPulse™ data product.

2.1.1 Light Source Performance Modulation

In order to enhance the characterization of specific patterning layer responses, Cymer developed advanced techniques for modulating light source beam and optical performance levels. Beam performance modulation methods enable engineering controlled variation of Divergence, Pointing, and Polarization from wafer to wafer. Optical performance modulations methods enable field level modulation of bandwidth (see Figure 3), wavelength and Energy stability across a wafer exposure. These techniques enable engineers to obtain an accurate on wafer response of 1D and 2D patterns to changes in light source performance.

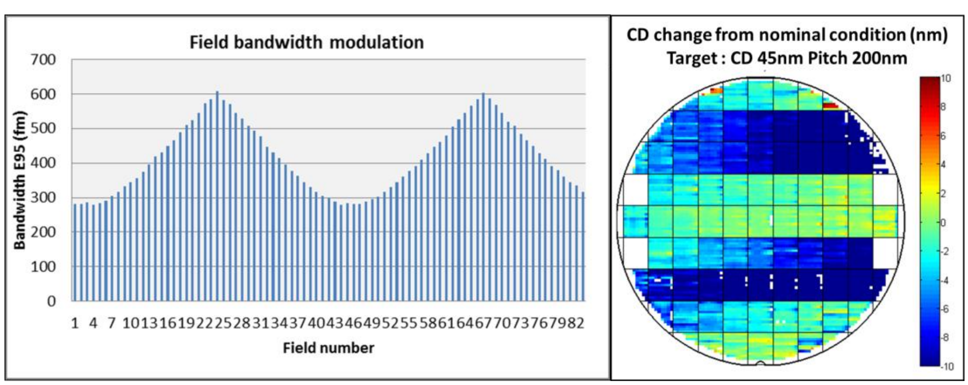


Figure 3. Cymer's modulation technique as demonstrated through on wafer response to E95 modulation per field

2.1.2 Beam Performance Conditions

The impact of light source beam performance on patterning was investigated using imec's 10 nm Contact Hole SRAM cell patterning process. The patterning process used the conditions shown in Table 1.

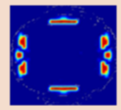
Parameter	Contact Hole Process
Freeform Illumination	
Process	NTD
NA	1.35
Polarization	XY
Track	Single Module Flow
Scanner	Single Chuck Flow

Table 1. Contact Hole patterning conditions

This process was an extension of the flow optimized by imec for the experimental study of source mask optimization for 22 nm SRAM cells[7]. The after develop inspection (ADI) target CD was 52 nm for a nested contact feature.

Changes in light source beam divergence, pointing and polarization were introduced using controlled engineering techniques and the beam response was measured using CASMM beam metrology, a key component of the SmartPulse product. Two different performance scenarios were reproduced by varying the beam alignment conditions as described in Figure 4; each scenario was selected to investigate the impact of end of life or beyond module performance on wafer patterning. Condition 1 modulated Horizontal and Vertical divergence and decreased polarization levels to represent a significant change in performance based on optical degradation modes. Condition 2 modulated Horizontal divergence to study the scanner illumination pupil response.

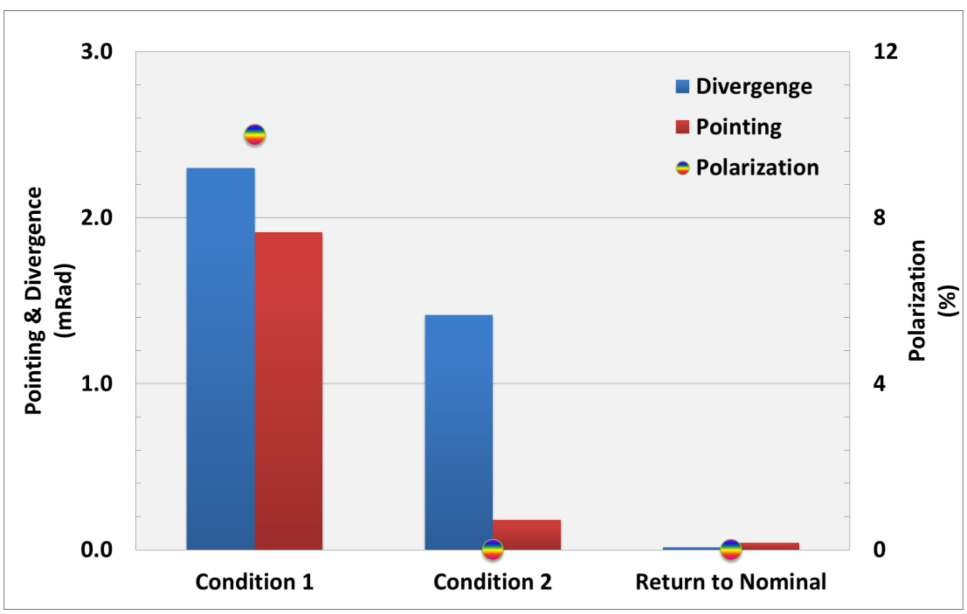


Figure 4. Relative change in beam performance for each modulation condition

These conditions were selected to replicate the experimental results previously collected at imec on a Cymer XLR-560i / ASML XT:1900i lithography cluster[12] on newer platforms that are being used for ≤ 20 nm node layer patterning.

The scanner illumination pupil response was measured using the ASML LUPI test and the raw data was analyzed to detect changes in intensity as a function of modulation conditions. The Contact Hole response to beam modulation was measured using top down CD-SEM metrology (Hitachi CG-5000).

2.1.3 Optical Performance Conditions

Light source bandwidth, wavelength and energy performance requirements have continued to be improved to enable the next generation of ArF immersion patterning[4]. The impact of E95 bandwidth variation on process performance has been previously reported in literature[14-23]. However, the majority of these studies have focused on the known E95 response differences between isolated and nested lines and spaces. This study focuses on the impact of light source performance on 10 nm node Metal 1 layer patterning, as 2D logic feature response to E95 bandwidth are expected to be more complex[12]. The patterning process used the conditions shown in Table 2.

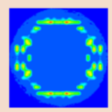
Parameter	Metal 1 Process
Freeform Illumination	
Process	NTD, LE^3
NA	1.35
Polarization	XY
Track	Single Module Flow
Scanner	Single Chuck Flow

Table 2. Metal 1 Patterning Conditions

The first split of an ArFi triple patterning 10 nm logic Metal 1 process layer, part of an imec process development test vehicle, was investigated in this study. Each exposure was performed on substrates optimized for the imec triple patterning process flow.

A selection of six hot spot (HS) structures was made based on the complexity of the OPC model of the test vehicle. Figure 5 shows the complete list of patterns studied in the investigation. A Line-Space structure was used as the anchor feature for the targeting of each wafer exposure (After Develop Inspection, ADI, 40 nm CD, 96 nm Pitch). The ADI CD targets for each hot spot are as shown and vary between 43 and 47 nm with each hot spot having a CD tolerance of ± 3 nm.

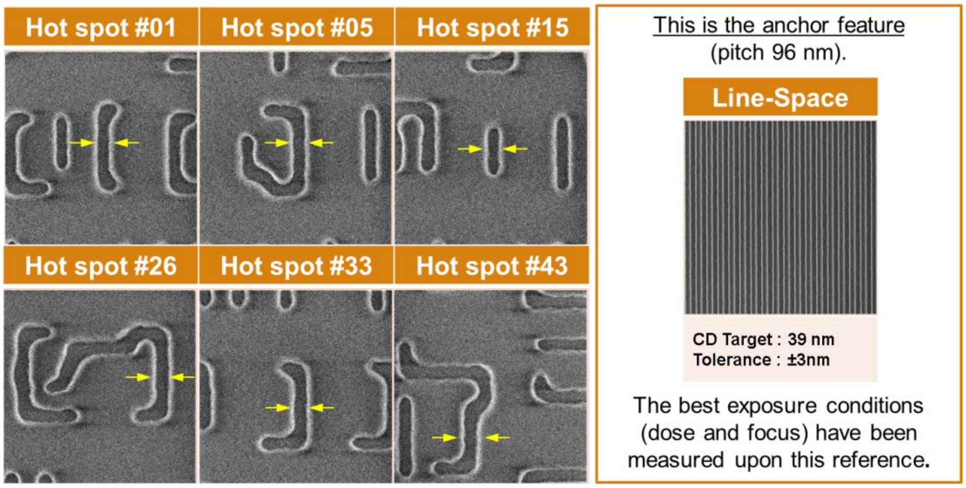


Figure 5. Hot Spot structures studied for the imec N10 Metal 1 layer

To study the impact of E95 bandwidth on hot spot patterning performance, multiple wafers were exposed at fixed E95 values. The bandwidth changes modulated per exposed wafer are shown in Figure 6. From a nominal E95 value of 300 fm, a range of -50 fm to +190 fm was sampled to explore nominal and excursion level bandwidth performance levels.

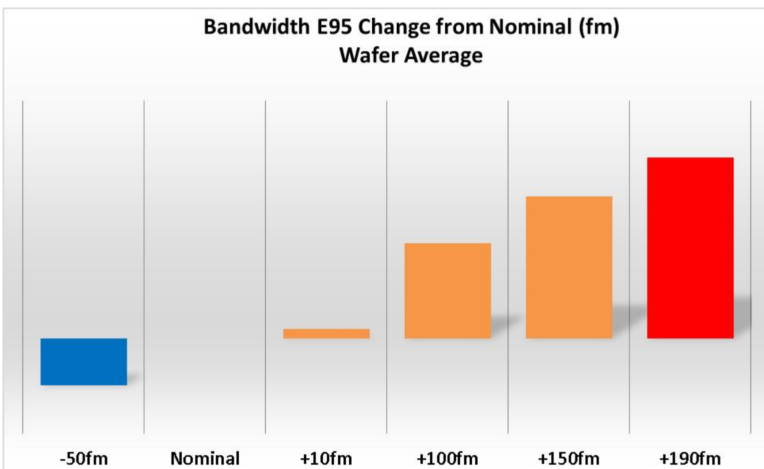


Figure 6. Optical performance modulation of E95 bandwidth (per wafer)

The hot spot response to E95 bandwidth modulation was measured using top down CD-SEM metrology (Hitachi CG-5000).

2.2 Experimental Results: Beam Performance Modulation

Beam modulation results revealed that changes in light source performance have measurable impacts on scanner illumination. Illumination pupil measurements obtained from the scanner (at the center of the slit) have been used to calculate the effective changes from the baseline comparing differences from each experimental condition to the baseline value using the raw image sensor data. The analysis identified measurable differences in a standard scanner annular illumination condition used for baseline performance monitoring. The change in annular integrated pupil energy variation is shown in Figure 7, a change from baseline performance of ~5% was observed for Condition 1.

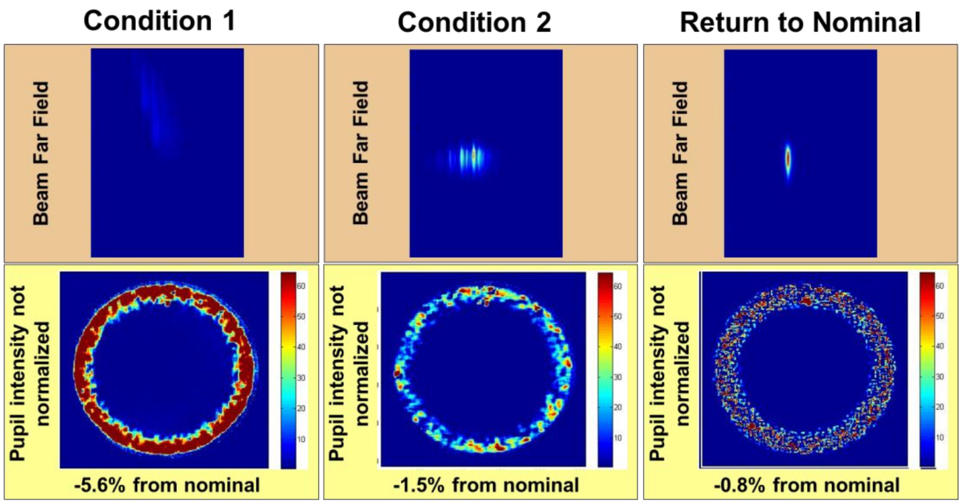


Figure 7. Pupil energy variation for each experimental and return to nominal conditions

Analysis of the process window using KLA-Tencor's ProData provided quantification of the effective CD changes due to dose and focus variation; the Contact Hole CD showed a measurable CD shift due to beam modulation (as shown in Figure 8).

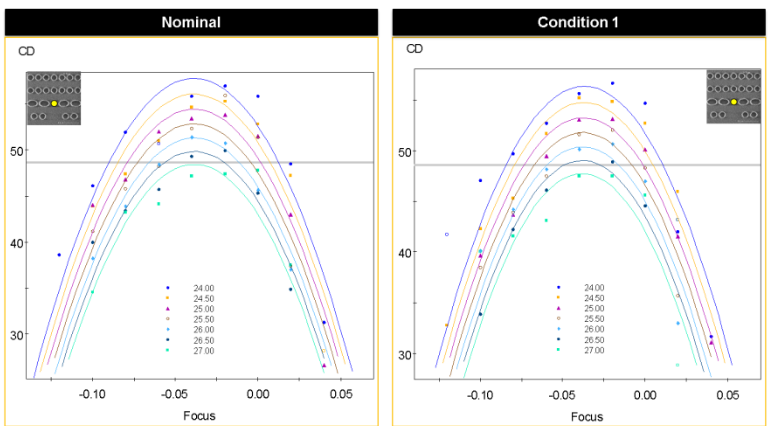


Figure 8. Contact hole measurement process windows comparison for baseline (left) and Condition 1 (right)

Condition 1 (Divergence, Pointing, and Polarization modulation) shows the largest impact; this is expected based on the previous studies where the wafer-plane intensity was measured and showed a significant impact for this experimental condition[11]. No significant shift in best focus was detected; compared to previous results[11], the impact is significantly less (see Figure 9), even with a change in CD target.

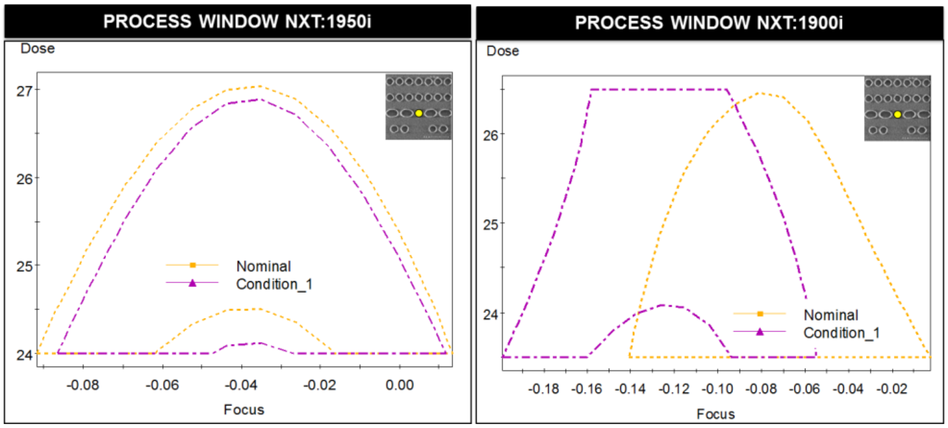


Figure 9. NXT:1950i (current study, left) and XT:1900i (previous study, right) PW response to beam modulation

The results suggest that patterning sensitivities to beam performance can be platform specific; additional studies are required to determine the correlation of platform design and tolerances with light source beam performance.

2.3 Experimental Results: Optical Performance Modulation

Wafer-to-Wafer E95 Bandwidth modulation was used to study the response of a set of 10 nm Node, Metal 1 layer hot spot structures. Unlike previous investigations, this study focused on the process window impact induced by E95 modulation. A quadratic response is observed for most of the hot spot structures sampled (see Figure 10).

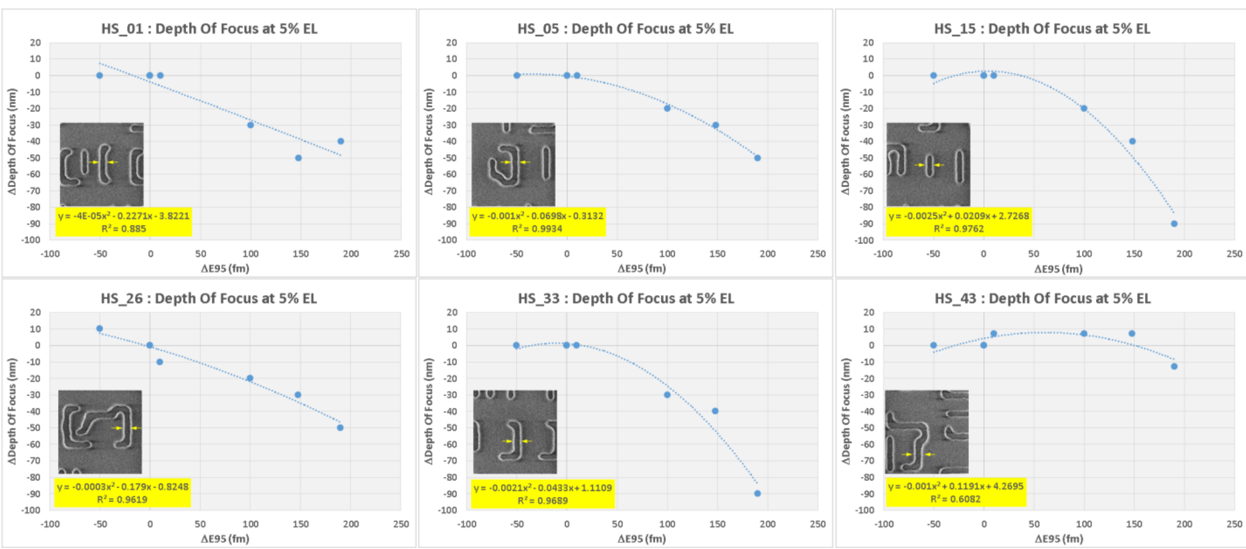


Figure 10. Hot Spot Process Window Results

Each of the six selected host spots exhibit different levels of response to E95 modulation. The impact of E95 on the process window for each hot spot is show in Table 3 in terms of Δ(Depth of Focus) / 50 fm E95. A nominal E95 change of 50 fm was used based on typical field performance of an NXT:1950i / XLR-660ix system.

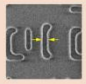
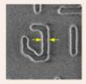
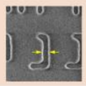
Hot Spot		∆ DoF nm / 50 fm E95
HS_01		-15.3
HS_05		-6.3
HS_15		-2.5
HS_26		-2.5
HS_33		-6.3
HS_43		7.7

Table 3. Hot Spot Process Window Results

Hot Spots HS_15 and HS_26 show limited response to an increase in E95. Conversely, the most significant impact to Depth of Focus (DOF) is observed for Hot Spot HS_01, which shows a response of -15 nm DOF / 50 fm E95. It should be noted that Hot Spot HS_26 data shows a slight improvement in DOF as bandwidth is decreased. The change in process window as a function of lower E95 bandwidth was investigated as part of another study[24].

3. LIGHT SOURCE MONITORING CAPABILITIES

In previous work[11-13], Cymer's SmartPulse platform was described as an enabling component of advanced lithography patterning control. The importance of monitoring key performance indicators of the light source continues to increase as the use of multiple patterning increases. Leading edge chipmakers use SmartPulse to enhance equipment monitoring and to execute correlation studies of light source performance with inline and end of line metrics. As demonstrated in this study, light source data for key optical parameters (e.g. bandwidth) enables accurate correlation and determination of patterning impacts.

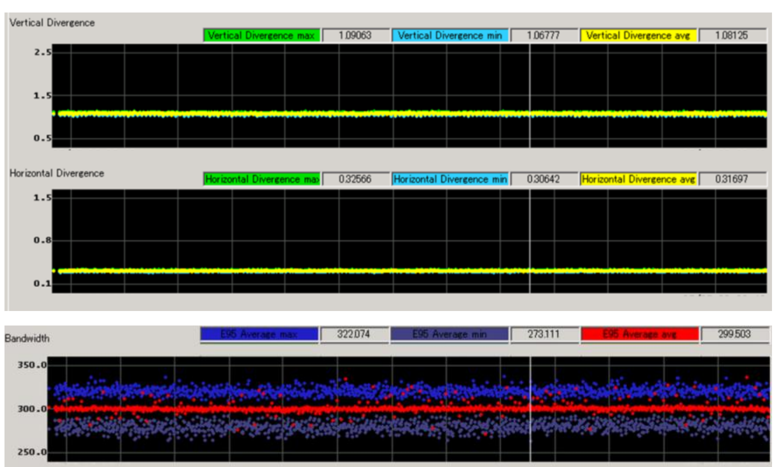


Figure 11. Baseline Beam (Divergence, Top) and Optical (E95, Bottom) performance from the imec cluster used in this study

Wafer statistics per exposure, as shown in Figure 11, enable rapid review of baseline performance and detection of performance deviations. Proactive characterization of patterning responses to light source performance enables the inclusion of light source data in process monitoring and excursion detection. Enhanced process monitoring can be enabled within the fab using SmartPulse's industry standard Interface A connectivity which provides optical and beam data to chipmaker FDC and/or SPC systems.

4. CONCLUSIONS

The on wafer impacts due to light source performance have been characterized through beam and optical parameter modulation experiment at imec's facilities in Leuven (BE). These techniques enable the measurement of the lithographic response of any pattern through the modulation of light source performance; for example, beam divergence and polarization and optical E95 bandwidth.

The beam experiment results obtained are consistent with what has been reported in the literature[11-12]; with on wafer process window results from Divergence and Polarization modulation showing measurable wafer patterning change for Contact Hole structures. However, unlike previous studies, the magnitude of the wafer responses was different on the NXT:1950i / XLR-660ix system compared to the previously studied XT:1900i / XLR-560ix system. Further study is needed to determine if there is a correlation among platform design, illuminator sensitivity, and/or system tolerances with light source beam performance.

Process window response to E95 Bandwidth was studied on 2D Metal 1 layer 10 nm Node structures as part of a next generation process node development characterization effort. Results from E95 modulation for the first split of a multiple patterning 10 nm logic Metal 1 layer showed significant, structure specific responses in Depth of Focus.

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